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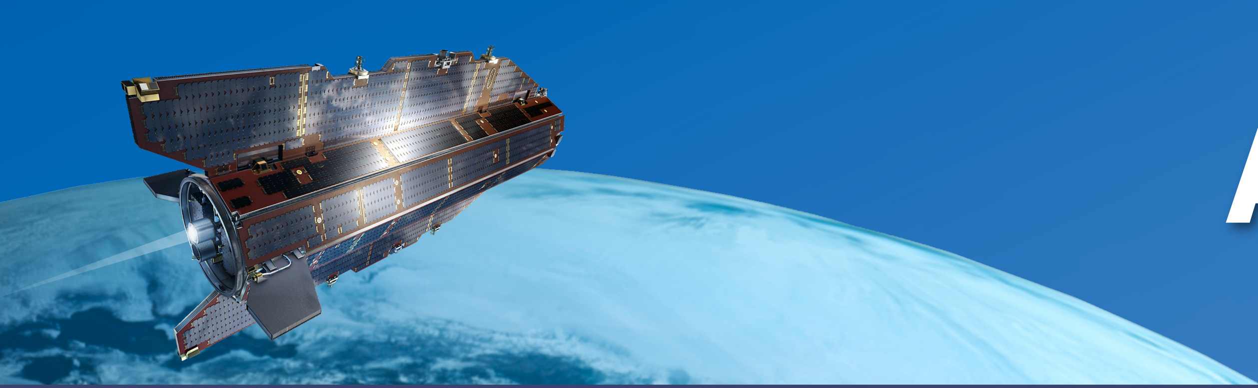
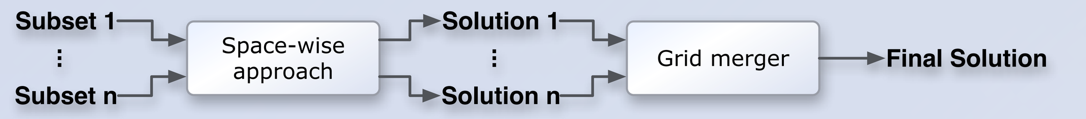


The model computed by the space-wise approach

The space-wise approach is a multi-step collocation procedure, developed in the framework of the GOCE data processing for the estimation of the spherical harmonic coefficients of the Earth gravitational field and their error covariance matrix.

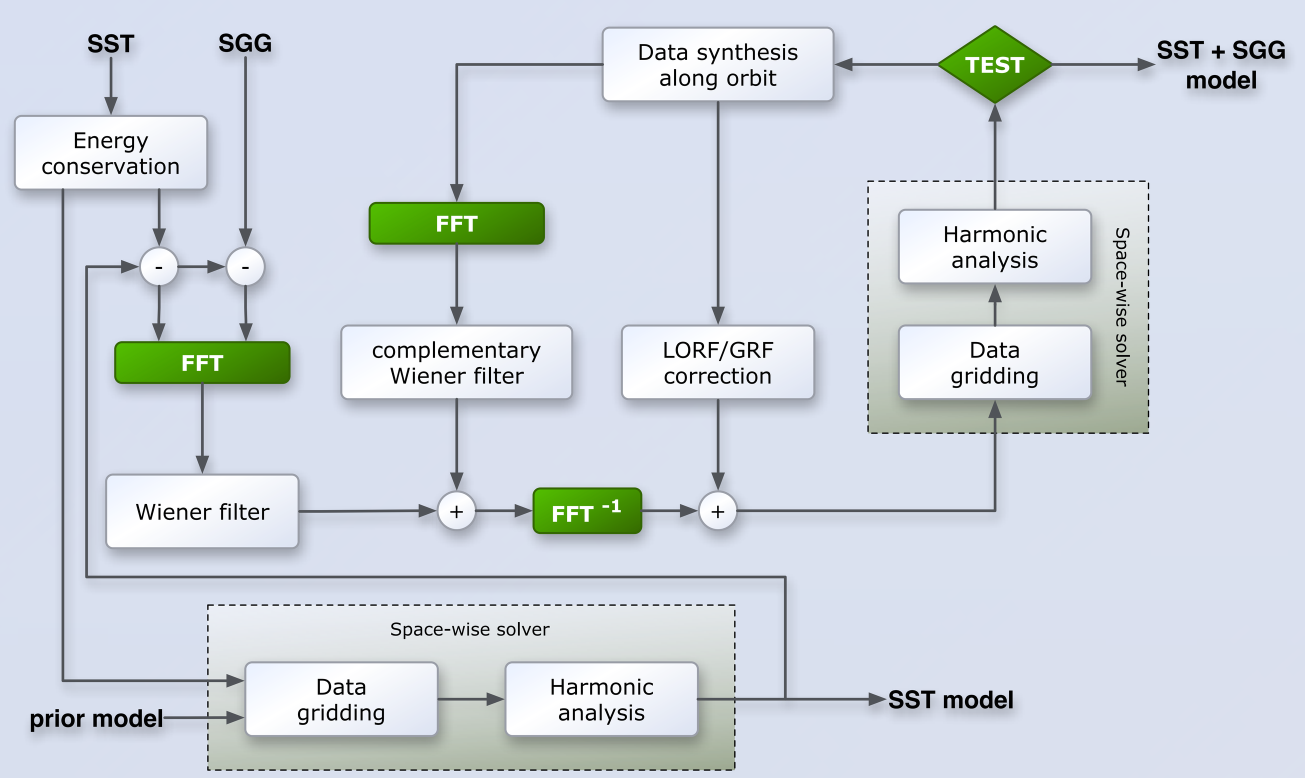
- Low-frequency part of the field: estimated from kinematic orbits based on satellite-to-satellite tracking (SST) data derived from the on-board GPS receiver (key method: energy conservation approach).
- High-frequency part of the field: derived by combining the estimated along-track gravitational potential with the satellite gravity gradients (SGG) observed by the on-board electrostatic gradiometer (key method: orbital Wiener filtering + collocation gridding).
- The full dataset is divided into different time periods with a maximum length of about two months of continuous observations based on the same gradiometer calibration.
- Grids of potential and second radial derivatives from each subset of data are merged together to obtain a unique estimation of the field.



- Spherical harmonic coefficients are computed by integrating estimated grids of potential and of its second radial derivatives at mean satellite altitude.
- Error covariance matrix of the estimated coefficients is derived by Monte Carlo simulations.

The model presented here is **a GOCE-only solution derived from about 8 months of data divided into 5 subsets** of different length, both GOCE orbits and gradiometer observations. The covered data period goes from 31 October 2009 to 6 July 2010.

The space-wise approach scheme



The rationale of this work

- The first release of the space-wise model (ESA Living Planet Symposium, Bergen, 2010) was a solution in between a pure GOCE-only model (TIM) and a combined model (DIR).
- Instead of continuing under this philosophy, it was decided to switch towards a space-wise GOCE-only model trying to remove the dependency on prior models based on external data.
- In order to obtain this results, criticalities had to be removed from the space-wise procedure:
  1. EGM08 had been used for SST data correction
  2. The GOCE quick-look model had been used, but it is not a GOCE-only model:
     - Reduced dynamic orbits from EIGEN5C
     - Polar gap regularization from EIGEN5C
  3. Since a prior model is removed before gridding to make collocation more efficient the residual signal has strong anisotropies especially due to the effect of polar gaps
- Pre-processing of the data has been semi-automatized
- A unique solution has to be produced starting from 8 months of raw data

Removing dependencies: error in the potential

The error covariance matrix of the estimated potential is computed as follows:

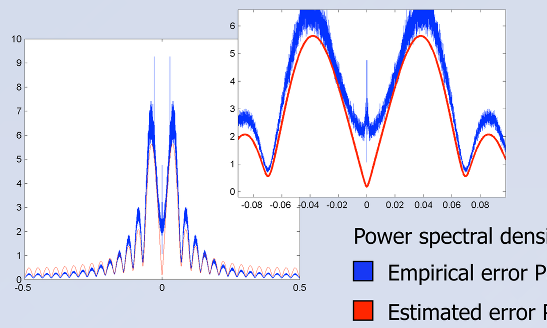
- Error variances of kinematic positions from PCV input files.
- Velocity error covariances (correlated up to 30 sec) propagating position errors through the used least-squares prediction moving window.
- Potential error covariances (correlated up to 30 sec) propagating velocity errors through the linearized energy conservation formula.

According to simulated data tests, accelerometer errors are not propagated to potential error.

This estimation introduces some discrepancies especially in the low frequencies.

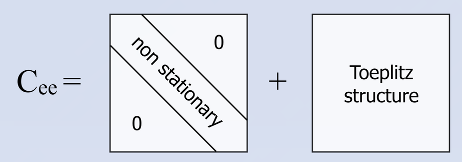
In the space-wise model of the "Bergen solution" the data of the potential were "adjusted" with synthesized data from EGM08.

➡ Strong external informations introduced at low-degrees (< 20-30)



Power spectral density.
Empirical error PSD wrt EGM08
Estimated error PSD from PCV assuming stationarity

Now data are unchanged, but the error covariance modeling is corrected to be consistent with the empirical covariance function.



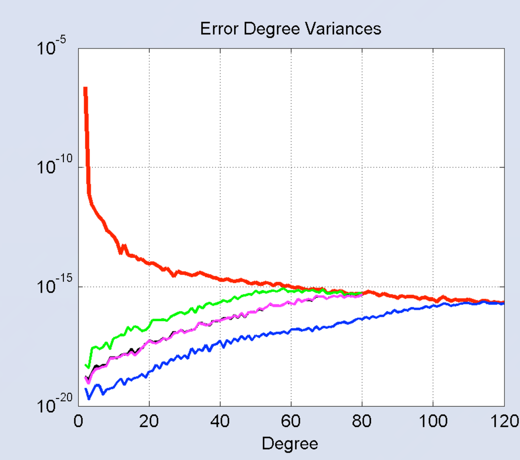
A Toeplitz matrix describing the corrections at low frequencies is added to the non stationary covariance matrix coming from the position error propagation.

Removing dependencies: a new prior model

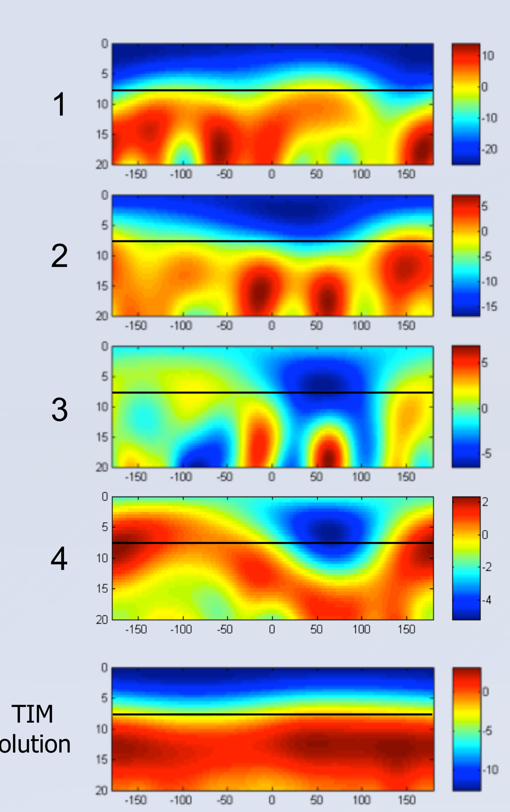
Since the quick-look model introduces some unwanted dependencies on external data, a new GOCE-only prior model has been developed.

The prior model is based on observations coming from the first two months of data and it is used for all the 5 intermediate solutions.

- Global collocation can work on a full signal, but a strong under-sampling (about 1:800) is needed for computational reasons. A first sufficient solution is obtained but its accuracy should be improved, especially in the polar areas.
  More important than the model accuracy, it is the estimate of a reliable error covariance which will be afterwards used for the Monte Carlo simulation.
  ➡ Degree variances are here appropriate for the full signal modeling.
- A step-wise global collocation procedure is implemented, considering the error covariance of the $(i-1)^{th}$ step as the signal covariance of the i^{th} step.
  - 8 collocations with data under-sampling at 1:800, each collocation working on data shifted by 100 epochs
  - 2 collocations with data under-sampling at 1:33 (data shifted by 33 epochs), but considering only data close to the poles (polar doughnut), thus improving the polar gap extrapolation
- A patch-wise collocation gridding is finally applied as in the baseline of the space-wise solution, using previously estimated prior model.



1 First global collocation solution (1:800)
2 8^{th} step-wise global collocation solution (1:100)
3 polar doughnut collocation solution (1:33)
4 patch-wise collocation solution (1:3, 20°x20°)



4 steps of the a-priori model - Geoid error [cm] from degree 2 to 20 in polar areas surroundings at different steps of the collocation solution.

Note the change of the scale at the different steps.

The error is in the end smaller than the corresponding two months TIM solution in polar areas from SST data.

Covariance modeling

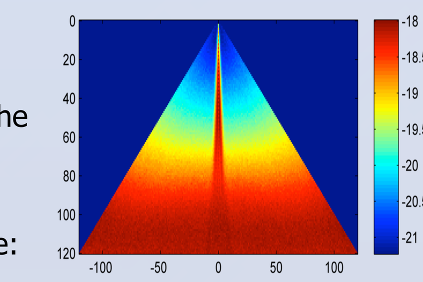
The estimated SST model is used as prior model for the gridding.

➡ the covariance of the residual signal has to be modeled.

In principle one has to propagate the full estimated covariance of the SST model to the different functionals (potential and gravity gradients).

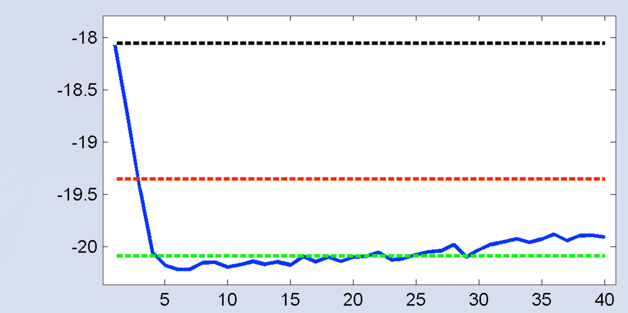
Different approximations are possible for the coefficients covariance:

1. block diagonal covariance matrix (order by order)
2. diagonal covariance matrix with different variances
3. diagonal covariance matrix based on degree variances



SST model coeff. variances
➡ Degree variances are too approximate to describe errors

In the implemented collocation gridding only degree variances are taken into account, this choice allows a lighter computation, but the rigid model of degree variances must be adapted to the anisotropic spectrum of the SST model errors.



Variances of cosine coefficients for degree 40
Variances
Maximum value of the variances
Degree variance
Degree median

We implemented two iterations of the space-wise scheme.

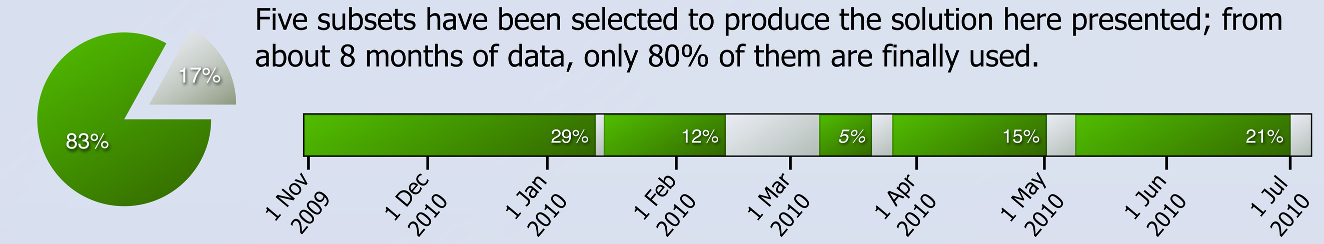
- The first one **overestimating degree variances**, so to allow data to better estimate low orders, i.e. make a good extrapolation in polar gaps and reduce border effects
- The second one **using degree medians**, so to better weight coefficients not affected by polar gaps

This is however an approximate solution. The most reasonable one would probably be to consider block covariances for low orders and variances for others.

From raw data to a unique solution

GOCE data are firstly divided in subsets of continuous observations with similar behavior, then the subsets are pre-processed in such a way to mark and remove outliers and fill small data gaps. Datasets with not enough valid data are disregarded.

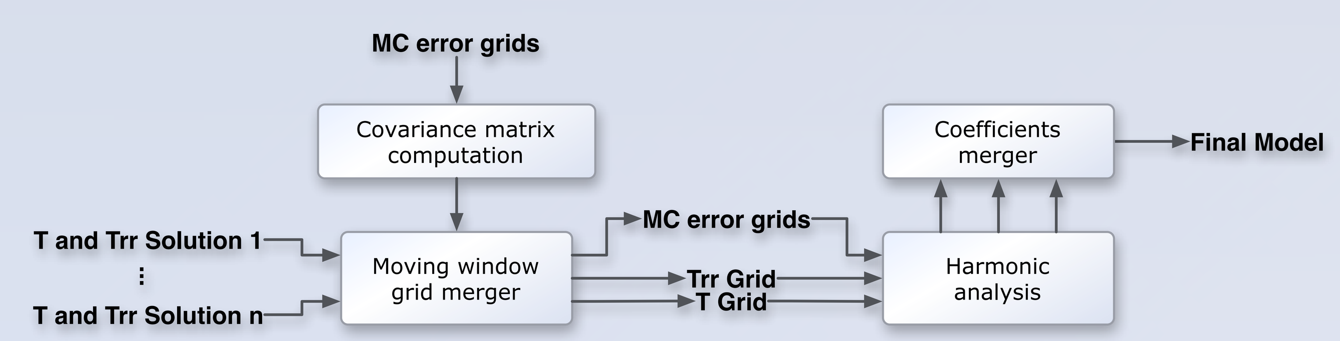
Five subsets have been selected to produce the solution here presented; from about 8 months of data, only 80% of them are finally used.



Subsets used for the solution
Discarded subsets of data
Considered subsets of data

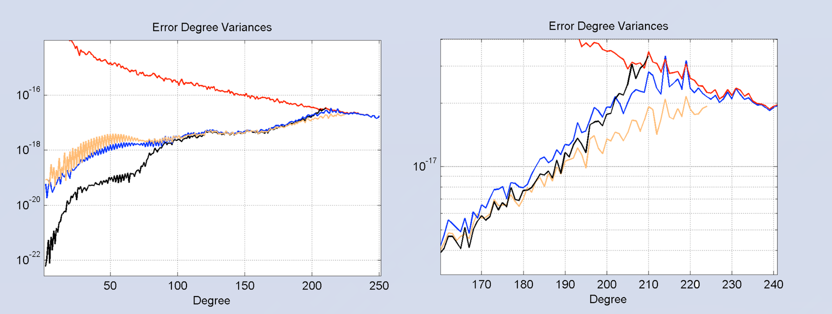
Different steps are then followed to obtain a unique solution

1. Each subset is processed following the space-wise approach producing grids of potential and second order radial derivative, plus Monte Carlo (MC) sample grids describing the error.
2. Merged grids of the two functionals are obtained by using a moving window and weighting data on the bases of MC error covariance matrices
3. A harmonic analysis is finally applied to these grids, obtaining two sets of coefficients that are merged by collocation based on the errors propagated from the MC sample grids.



Two months solution comparison

As a result of all the changes made in the approach the space-wise approach now able to produce GOCE only solutions; a comparison of a new model (computed from two months of data) highlights its new characteristics.



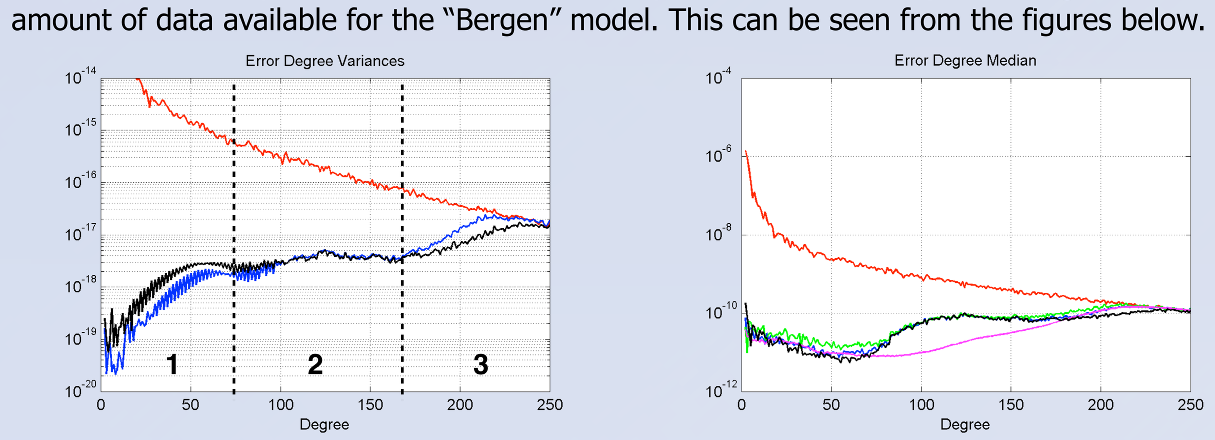
With the "new" solution:

- good estimation of the low orders
- over-regularization at the highest orders.

Space-wise "Bergen" solution
Space-wise "new" solution
Time-wise solution

Final results and conclusions

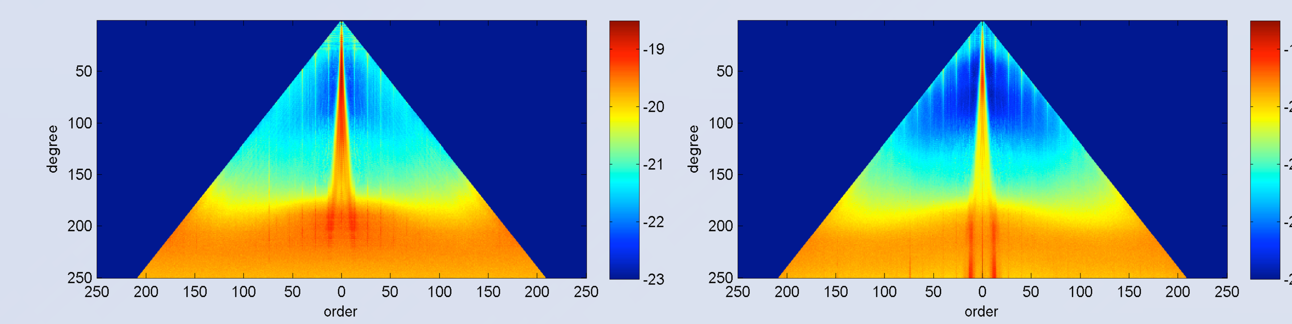
The new GOCE only model improves the accuracy of the estimation by exploiting three times the amount of data available for the "Bergen" model. This can be seen from the figures below.



Error degree variances with respect to EGM08
Space-wise solution
Time-wise solution

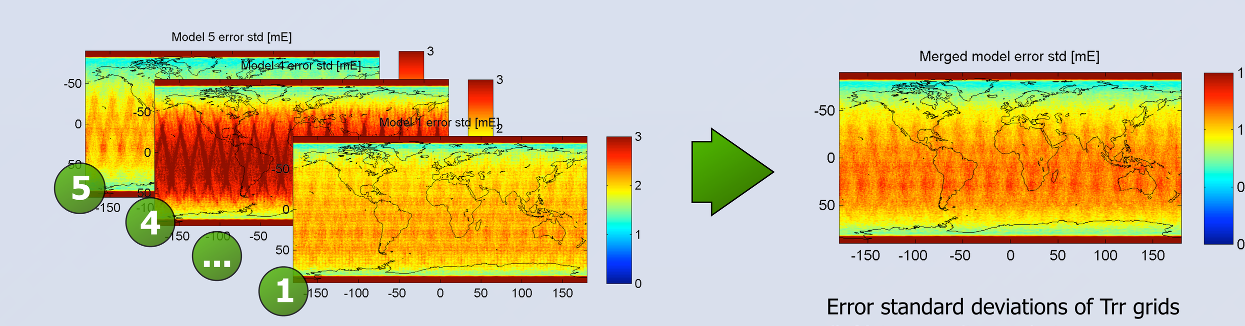
1. Polar gaps effect
2. Dominance of EGM08 errors
3. Regularization effect

Error degree median with respect to EGM08 (not affected by polar gaps)
Space-wise two months solution
Space-wise solution
Time-wise solution
error prediction by Monte Carlo



Improvement in terms of coefficients error standard deviation from the two months solution to the final one.
Note that the effect of the polar gaps on the low order coefficients is under-estimated after merging the intermediate solutions.

Grids of GOCE observables are computed at satellite altitude and their error covariances are used for merging intermediate solutions, these grids could be used for geophysical applications too.



Error standard deviations of Trr grids
(left) intermediate solutions
(right) merged solution

The space-wise approach is now producing GOCE-only models, and in particular a solution based on the first delivered eight months has been computed.
An improvement of the model can be achieved by properly modeling the residual signal covariance so to better control the regularization at the highest degree.

The error commission up to degree 200 in the latitude interval -80 < phi < 80 is:

- about 6 cm in terms of geoid undulations,
- about 1.6 mgal in terms of gravity anomalies.

The maximum degree of the model is 240.

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